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# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1529

AN INVESTIGATION OF MECHANICAL PROPERTIES OF HONEYCOMB  
STRUCTURES MADE OF RESIN-IMPREGNATED PAPER

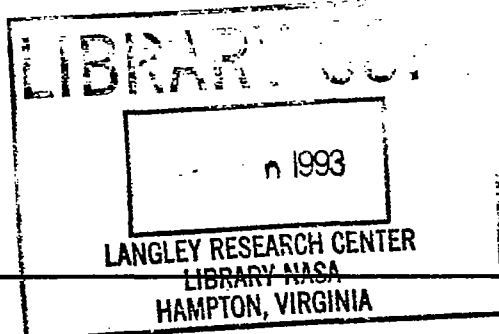
By C. B. Norris and G. E. Mackin

Forest Products Laboratory



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AN INVESTIGATION OF MECHANICAL PROPERTIES OF HONEYCOMB

STRUCTURES MADE OF RESIN-IMPREGNATED PAPER

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SUMMARY

An investigation was made to determine the order of magnitude of the important mechanical properties of honeycomb-like structures. The modulus of rigidity, shear stress at proportional limit, and shear strength of resin-impregnated paper honeycomb structures compare favorably with those of balsa wood. The modulus of elasticity, compressive stress at proportional limit, compressive strength, and tensile strength of resin-impregnated paper honeycomb structures are lower than those of balsa wood but considerably higher than those of cellular cellulose acetate and cellular hard rubber.

INTRODUCTION

The design of aircraft for travel at high speeds may conveniently employ stiff but light panels as the skin of the structure. Panels of this kind can be made by bonding a thin sheet facing of a high-strength material, such as aluminum, or glass-fiber laminate, to each side of a core of light material, such as balsa wood. Combinations of sheet materials of this nature are called sandwich constructions.

The functions of the core of a sandwich construction are to space the facings so that a high stiffness of the construction is obtained and to support the facings so that they are elastically stable when highly stressed. The lightest material that has sufficiently high mechanical properties to accomplish these purposes in any particular sandwich construction is the best core material, if its other properties, such as durability and resistance to moisture, are satisfactory.

The important mechanical properties of a core material are tensile strength, compressive strength, and modulus of elasticity in the direction perpendicular to the plane of the facings; shear strength in planes parallel to the facings; and modulus of rigidity measured in planes perpendicular to the facings. These properties should be as low as is practical in the interest of light weight of the entire sandwich construction. The exact minimum values of these properties required for satisfactory sandwich constructions are not yet known, but it is

assumed that they can be expressed in terms of the material and thickness of the facings and the type and amount of load the construction is designed to carry. Balsa wood was the first successful one.

In a search for new core materials the Materiel Command of the Army Air Forces published a list of values that, from their experience seemed desirable. Their requirement that the materials be very light (density, 0.05 to 0.15) practically restricts the choice to those of cellular composition. Various resins and rubber compounds formed into masses of cells by special methods have been tested. Some of these materials show promise, but most of them exhibit inadequate mechanical properties. Sheet materials built into honeycomb-like structures show marked promise and have, therefore, aroused great interest.

The work reported herein was undertaken to determine the order of magnitude of the important mechanical properties of honeycomb-like structures. Such materials were not commercially available at the time the work was started and, therefore, methods of making them were developed. Resin-impregnated papers were chosen as a convenient medium, and short studies were made of the effect of the properties of the papers and the various resins on the mechanical properties of the honeycomb structures. These studies were based upon compressive strength and resulted in the choice of a paper-resin combination that was employed in a more thorough evaluation of mechanical properties. These included strength, stress at proportional limit, and modulus of elasticity in compression in the direction of each of three elastic axes and in shear associated with the axes of the cells and with each of the other two elastic axes, and the strength and stress at proportional limit in tension in the direction of the axis of the cells. These properties were obtained for materials of five different apparent specific gravities.

This work was conducted at the Forest Products Laboratory under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

## DESCRIPTION OF MATERIALS

### Papers and Resins

Ten different papers were employed in making the honeycomb structures that were tested. They are given in table 1 with some of their properties. The papers are designated by letters from A to J, followed by a number indicating their nominal thicknesses in mils. These papers were corrugated, treated with resin, and assembled into honeycomb structures, as described in the appendix. Thirteen different resins were employed. They are designated by letters from A to M and are given in table 2. The honeycomb structures made of these papers and resins are

designated by a letter followed by a number and another letter. The first letter refers to the paper employed and the number indicates its nominal thickness in mils. The second letter indicates the resin used. In some of the designations two letters follow the number; the first of these indicates the resin used in treating the paper before corrugation and the second, that used in assembly of the honeycomb structure as described in the appendix.

Descriptions of the various papers used and some of their properties, noted in the manufacture of the honeycomb structures, follow.

Chestnut chip paper A9.— This was a commercial 9-mil paper. It corrugated well and the corrugations were rigid, and therefore it was easily fabricated into honeycomb structures without undue misalignment of laminations. It could be impregnated with resin but not uniformly, probably because it was rosin-sized during its manufacture.

Mitscherlich sulfite paper B4.— This was made on the Forest Products Laboratory paper machine (fig. 1) from pulp purchased for the purpose. It corrugated readily, but the corrugations were not rigid, and therefore a large amount of difficulty was experienced in fabricating honeycomb structures from it. The cells of the structures obtained were distorted and uneven. The paper impregnated well, and a relatively uniform distribution of resin was obtained.

Kraft paper containing glass fibers C5.— This was made on the Forest Products Laboratory paper machine from pulp manufactured at the Laboratory. Glass fibers having a diameter of 4 to 5 microns and lengths of  $5/8$  inch were added to the pulp in the amount of 10 percent by weight. These fibers were probably shortened by the beating process. This paper had a marked tendency to flatten after it was corrugated, and the cells of the honeycomb structures made of it were distorted in shape. Similar paper having a glass-fiber content of 20 percent could not be satisfactorily corrugated.

Kraft papers D4, E6, F8, and G10.— These were made on the Forest Products Laboratory paper machine from pulp manufactured at the Laboratory. They corrugated satisfactorily with the exception of paper D4, which was not thick enough to hold its corrugations satisfactorily. Uniform impregnations with resin were easily attainable.

Kraft papers H3 and I4.— These were obtained from a commercial manufacturer. They were impregnated with resin A before they were corrugated. The corrugations were rigid because of the resin treatment, in spite of the thinness of the paper. Subsequent impregnation with contact resin was satisfactory.

Kraft paper J6.— This was a bulky, soft commercial paper of unknown origin. It corrugated satisfactorily and was readily impregnated with resin.

All the resins used were commercially available and are described in table 2.

### Honeycomb Structures

The honeycomb structures were made from corrugated paper impregnated with resin as described in the appendix. The distances between adjacent nodes (b in fig. 2) of the corrugations varied from 0.25 to 0.28 inch, and twice the amplitude (c in fig. 2) of the corrugations varied from 0.077 to 0.093 inch. The corrugations in a sheet were laid parallel to those of adjacent sheets, as shown in figure 3, to form the honeycomb structures. Twenty different honeycomb structures of this type were fabricated and tested.

### METHODS OF TESTS

#### Compression Tests

Specimens for compression tests were cut from the honeycomb structures. Those for the determination of properties in the direction of the length of the cells were cut 8 inches long in that direction and 2 by 2 inches in cross section, as shown in figure 4. Those for the determination of the properties in directions perpendicular to the direction of the length of the cells and parallel and perpendicular to the planes of the corrugated sheets were cut 6 inches long in the direction of the stress and 2 by 2 inches in cross section.

The specimens were tested in a hydraulic testing machine at a constant rate of head travel. Deformations were measured by means of a Martens' mirror compressometer of 2-inch gage length. Load-deformation curves were plotted from which values of modulus of elasticity and stress at proportional limit were obtained. Maximum loads were recorded, and the maximum stress was computed.

#### Tension Tests

An apparatus (fig. 5) designed for testing low-density materials in tension was employed. The specimens were cut from the honeycomb structures and were 1 by 1 inch in cross section and 1/2 inch long in the direction of the length of the cells. These specimens were glued to 1-inch cubes, as shown in figure 5, and assembled in the apparatus. The load was applied through the universal joints illustrated in figure 5 by means of a hydraulic testing machine; thus an even distribution of the load over the cross section of the specimen was obtained. The maximum load was recorded.

An exploratory series of specimens was made to determine a satisfactory technique for bonding the specimens to the aluminum blocks. The metal primers and secondary glues given in table 2 were employed. The methods used and the results obtained are given in table 3. Figure 6

shows the types of failure obtained. The letters in this figure refer to the letters in the first column of table 3. The aluminum blocks were coated with a metal primer. After the metal primer had dried, the specimens were fixed to the primed blocks by means of a secondary glue. It was found that either of the metal primers O and Q with secondary glue S produced satisfactory results if properly used.

### Shear Tests

The apparatus employed in the shear tests was designed for testing low-density materials. It is shown in figures 7 and 8. Test specimens were cut from honeycomb structures and were 6 inches long, 2 inches wide, and 1/2 inch thick in the direction of the length of the cells. Specimens of two kinds were obtained - those in which the planes of the corrugated paper were parallel to the length of the specimen and those in which these planes were perpendicular to the length. Side and end plates were glued to the specimen, as illustrated in the figures. Metal primer P and secondary glue S (table 2) were found to be suitable for this purpose.

The assembled specimen was placed in a hydraulic testing machine, as illustrated in figure 8. The longitudinal movement of one of the side plates with respect to the other was measured by means of the dial shown. Readings of the dial were taken at regular increments of the load until the stress at proportional limit had been exceeded. Readings were then discontinued to avoid damage to the dial. The maximum load was recorded. Stress-deformation curves were plotted from the data obtained and values of modulus of rigidity and stress at proportional limit determined.

### ANALYSIS OF RESULTS

It was assumed that all the important mechanical properties of honeycomb structures are roughly proportional to their compressive strengths in the direction of the length of the cells, and therefore tests to determine the effect of the use of various papers, resins, amounts of resin, and methods of manufacture were limited to compression tests. These tests led to the choice of a good structure and the other important mechanical properties of this structure were determined. Tests were made on samples of this best structure fabricated to five different specific gravities.

#### Adjustment of Results of Compression Tests

##### to a Common Specific Gravity

For the comparison of the compressive strengths of honeycomb structures made of various materials, it is necessary to adjust the values

obtained from tests to a common specific gravity. It was found possible to estimate the change in compressive strength due to a change in the thickness of the cell walls, all other dimensions of the cells remaining constant. Thus if the compressive strength of a particular honeycomb structure is known, the strength of another structure identical to the first except for the thickness of the cell walls can be estimated. It can also be shown that the apparent specific gravities of two such structures are practically proportional to the wall thicknesses of their cells, and thus a relation is obtained between the compressive strength and the apparent specific gravity.

It has been shown that the specific compressive strength of a honeycomb structure is given by the equation (reference 1)

$$p_s = \frac{p_p^{2/3} (KE)^{1/3}}{g} \left( \frac{h}{a} \right)^{2/3} \quad (1)$$

where

$p_s$  specific strength (compressive strength divided by apparent specific gravity)

Of the material of which the honeycomb structures are made,

$p_p$  proportional limit in compression

$E$  modulus of elasticity

$g$  specific gravity

$h$  thickness

$K, a$  constants depending on shape and size of cells

Thus for two structures which are identical except for the thickness of the cell walls

$$\frac{p_{s1}}{p_{s2}} = \left( \frac{h_1}{h_2} \right)^{2/3} \quad (2)$$

Figure 2 is a sketch of an element of a honeycomb structure. The volume of this element is

$$v = (c + h)bd \quad (3)$$

and its specific weight is

$$w_s = shdg \quad (4)$$

Its apparent specific gravity is, therefore,

$$g_a = \frac{shdg}{(c + h)bd} \quad (5)$$

The ratio of the apparent specific gravities of two such structures which are identical except for wall thickness is

$$\frac{g_{a1}}{g_{a2}} = \frac{h_1}{h_2} \frac{c + h_2}{c + h_1} \quad (6)$$

Now, if the wall thicknesses are small compared with the cell size (which is usually the case) and the two thicknesses are not very different,

$$\frac{g_{a1}}{g_{a2}} = \frac{h_1}{h_2} \text{ (approx.)} \quad (7)$$

By combining equations (2) and (7), the following equation is obtained:

$$\frac{p_{s1}}{p_{s2}} = \left( \frac{g_{a1}}{g_{a2}} \right)^{2/3} \text{ (approx.)} \quad (8)$$

The fact that the ratio of the two apparent specific gravities is raised to a power less than unity increases the accuracy of the approximation.

The ratio of the specific compressive strengths of two honeycomb structures that are identical except for the thickness of their cell walls thus is found to vary approximately directly with the two-thirds power of their apparent specific gravities. This relation was used to adjust values obtained from tests to a common apparent specific gravity. It is estimated that its use in this report led to errors of only a few percent.

#### Effect of Resin Content

The resin content of the impregnated paper of which the honeycomb structures were made was limited by practical considerations. It was found that resin contents below 45 percent were not sufficient to produce satisfactory bonds between the laminations and that if more than 55 percent resin was used some of it flowed out of the structure while it was being cured. Three honeycomb structures (A9F) were tested in



compression. In their manufacture, chestnut chip paper (A9) was employed with resin F. Each structure contained a different percentage of resin by weight - 45, 50, and 55 percent. The results of the tests are given in table 3. It may be noted that the specific compressive strength corrected to a common specific gravity of 0.153 (fifth column of table 4) increased as the resin content increased. However, the increase in strength of the structure impregnated with 55 percent resin over that impregnated with 50 percent is small. It was assumed that these results would apply approximately to all the papers and resins employed in this report and a standard resin content of between 50 and 55 percent was adopted.

#### Effect of Kind of Paper Employed

Seven different honeycomb structures made of papers A to G and resin I were tested in compression. The results of these tests are given in table 5. The specific compressive strengths adjusted to a specific gravity of 0.153 are given in the seventh column of table 5. It may be noted that the structure A9I made of the chestnut chip paper is a little weaker than the others. The other papers, including the kraft with glass fibers, were all of substantially the same strength.

#### Effect of Kind of Resin Employed

Seven different honeycomb structures made of chestnut chip paper A9 and resins B, F, G, H, I, J, and M were tested in compression. The results of these tests are given in table 6. The specific compressive strengths adjusted to a specific gravity of 0.153 are given in the sixth column of table 6. It is evident from these data that the compressive strength was definitely affected by the kind of resin employed in the manufacture of the structures. The best results were obtained with resin F.

#### Effect of Partial Treatment of Paper

##### with Resin Prior to Corrugation

As noted in the appendix, some of the papers, particularly the thinner ones, did not corrugate well. They tended to flatten after corrugating. Such papers can be stiffened by a partial resin impregnation before corrugation. Two honeycomb structures were made in this way and tested in compression. Two lots of paper D4 were impregnated with resin A, the first with 11 and the second with 20.6 percent. The papers were then corrugated and made into honeycomb structures by means of a sufficient amount of resin J to make up a total resin content of 55 percent. For purposes of comparison, a third lot of the same paper was corrugated without previous impregnation with resin A and made into

a honeycomb structure with resin J in the amount of 55 percent. The results of compressive tests on these three structures are given in table 7. The data indicate that the optimum amount of resin A is about 11 percent.

### Important Mechanical Properties of

#### Strongest Honeycomb Structure Obtained

The strongest honeycomb structures were obtained by the use of kraft papers treated with about 11 percent of resin A before corrugation and with a sufficient quantity of resin F during the manufacture of the structure to obtain a total resin content of from 55 to 60 percent. Five different structures were made; two structures of H3AF, the first having a specific gravity of 0.070 and the second 0.080, and one each of I4AF, J6AF, and E6AF having specific gravities of 0.100, 0.106, and 0.138, respectively. Compression tests were made on 10 specimens cut from each of these structures, 4 in the direction of the cells, 4 parallel to the plane of the corrugated paper and perpendicular to the direction of the cells, and 2 perpendicular to the plane of the corrugated paper. Tension tests were made on about 15 specimens cut from each of the structures. Shear tests were made on 8 specimens cut from these structures, 4 such that the deformation is associated with the direction of the length of the cells and the direction perpendicular to that direction and parallel to the corrugated sheets, and 4 such that the deformation is associated with the direction of the length of the cells and the direction perpendicular to the corrugated sheets.

The average results are given in table 8. They illustrate the values of mechanical properties that well-made honeycomb structures of resin-impregnated paper may be expected to exhibit. An exhaustive study of all obtainable resins and variations of them was not made and higher values of the mechanical properties may be attainable. The properties of honeycomb structure I4AF having a specific gravity of 0.100 are compared in table 9 with those of balsa wood, cellular cellulose acetate, cellular hard rubber, and honeycomb glass cloth - all of approximately the same specific gravity. Of these materials balsa wood has properties of the highest values. The shear properties of the honeycomb paper structure compare favorably with those of the balsa wood and the honeycomb glass cloth. The values of the other properties of the honeycomb paper are below those of the balsa wood and the honeycomb glass cloth but above those of cellular cellulose acetate and cellular hard rubber.

### CONCLUSIONS

From an investigation to determine the order of magnitude of the important mechanical properties of honeycomb-like structures, the following concluding statements may be made.

The modulus of rigidity, shear stress at proportional limit, and shear strength of resin-impregnated paper honeycomb structures compare favorably with those of balsa wood. The modulus of elasticity, compressive stress at proportional limit, compressive strength, and tensile strength of resin-impregnated paper honeycomb structures are lower than those of balsa wood but considerably higher than those of cellular cellulose acetate and cellular hard rubber.

Forest Products Laboratory

Madison, Wis., August 19, 1946

## APPENDIX

## FABRICATION OF HONEYCOMB CORE MATERIAL FROM CORRUGATED PAPER

Various methods for fabricating low-density honeycomb core materials were investigated and resulted in the establishment of a standard procedure consisting of: (1) Partial impregnation of paper with water-soluble phenol resin, (2) corrugation of the impregnated paper, (3) application of contact-type resin to the corrugated paper, (4) assembly into a honeycomb-type structure, and (5) curing the assembled core.

Core materials having a wide range of specific gravities and strengths were produced by varying the resin content, thickness of paper, or both. Details of the established procedure are given in the following sections.

## Partial Impregnation with Phenol Resin

Early experiments showed that ordinary kraft paper would not retain the contour of the corrugations during subsequent resin treating and assembly operations. It was found, however, that if the paper was impregnated with about 10 percent of water-soluble phenol resin before corrugating, the contours of the individual corrugated flutes were retained throughout the subsequent fabricating operations. This effect was especially noticeable when light-weight papers were used to produce core materials of very low density. It was also observed that this partial impregnation produced core materials having much higher compressive strengths than were obtained with untreated paper. The partial impregnation of the papers used in making honeycomb cores was accomplished on the Laboratory experimental impregnator (fig. 9).

## Corrugating of Resin-Treated Paper

The resin-treated paper was corrugated on a Forest Products Laboratory corrugating machine (fig. 10) equipped with "B" flute rolls (the smaller of two sizes of flutes commonly used in corrugating paper for use in shipping containers). The temperature of the corrugating rolls was maintained at about 160° C.

For convenience in handling, the corrugated paper was cut into sheets and immediately "nested" flat in order to minimize subsequent dimensional change. Stacks of the nested paper were then placed in an oven at 125° C for about 6 hours to cure the phenol resin. After this treatment, the contour of the corrugations was not seriously affected by handling during subsequent fabrication operations.

### Application of Contact-Type Resin

Apparatus was designed and built for applying a controlled amount of contact resin to the corrugated paper (fig. 11). This apparatus consisted of a level plane surface on which a film of resin was distributed uniformly by means of a doctor blade. Adjustment of the clearance between the surface and the edge of the doctor blade was provided for control of the thickness of the resin film, which in turn controlled the resin content of the finished core. The corrugated paper was placed on the resin film, thus transferring the resin to the nodes of the corrugated paper. A slight pressure was used to insure adequate contact of the paper with the resin. A specified time interval of from 5 to 10 seconds was given to permit sufficient penetration of the resin into the paper. The resin content was determined by weighing test sheets of the paper before and after treating. Accuracy of resin content to within  $\pm 1$  percent was obtained by this method.

### Assembly of Core Material

The resin-treated corrugated paper was assembled into cores by placing layers of the paper with the nodes of each ply, making contact with the nodes of adjacent plies.

Short sections of paper straws having an outside diameter of 0.150 inch were placed at intervals along the sheets and served as keys to maintain the alignment of the corrugations. The ability of the straws to deform slightly to accommodate the shape of the flutes and the advantage of using disposable keys made the paper straw more desirable than metal rods used in earlier experiments. Core blocks approximately 4 feet long, 1 foot wide, and  $2\frac{1}{2}$  inches thick were easily produced by this procedure.

In order to control the uniformity of core thickness and to insure adequate contact between laminations, the assembled core was placed between parallel cauls separated by spacers at the corners. Uniform distribution throughout the paper of the contact-type resin was obtained during a diffusion period of 30 minutes at a temperature of 50° C before curing the resin. Equivalent results, however, were obtained at room temperature after longer periods of diffusion.

The final cure of the contact resin was obtained by placing the assembled core in a forced-air oven. Provision was made in this oven to force air at 125° C through the flutes in order to reduce the time required for cure. This was necessary because of the poor heat transfer of this type of material. In general, a cure time of about 2 hours was required for the honeycomb cores.

The finished honeycomb core material was cut into the desired thickness for sandwich constructions by sawing strips either on a band

or circular saw. Best results were obtained by using a saw having 4 or  $4\frac{1}{2}$  teeth per inch and operated at a speed of from 4,000 to 5,000 feet per minute.

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TABLE 1. - PROPERTIES OF PAPERS USED IN MAKING HONEYCOMB CORE MATERIAL

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Designa- tion	Type of paper	Ream weight 25 by 40 in.-500 (lb)	Thick- ness (mils)	Density	Tensile strength across machine (psi)
A9	Chestnut chip	117.6	8.5	0.70	1950
B4	Mitscherlich	46.2	4.0	.65	3160
C5	Kraft plus 10 percent glass fiber	57.9	4.9	.66	4310
D4	Kraft	68.4	4.1	.92	8500
E6	Kraft	95.8	5.7	.92	6500
F8	Kraft	119.8	7.9	.83	6190
G10	Kraft	155.0	9.8	.88	5600
H3	Kraft	34.8	2.8	.69	5200
I4	Kraft	57.1	4.1	.77	5550
J6	Kraft	60.3	5.9	.57	3540



TABLE 2. - KEY TO RESINS USED IN HONEYCOMB CORES

Designation	Description
	Treating Resins
A	Water-soluble phenol resinoid
B	Unsaturated polyester low-pressure laminating resin
C	Alcohol-soluble phenol-formaldehyde resin
D	Alcohol-soluble phenol-formaldehyde resin
E	Alcohol-soluble phenol-formaldehyde resin
F	Addition-type copolymer low-pressure laminating resin
G	Unsaturated polyester low-pressure laminating resin
H	Unsaturated polyester low-pressure laminating resin
I	Unsaturated polyester copolymer low-pressure laminating resin, medium viscosity
J	Unsaturated polyester copolymer low-pressure laminating resin, high viscosity
K	Beater-type phenol resin with low softening point
L	Beater-type phenol resin with medium softening point
M	Diallyl phthalate polymer





TABLE 2. - KEY TO RESINS USED IN HONEYCOMB CORES - CONCLUDED

Designation	Description
	Metal primers
N	Hot-setting modified thermoplastic resin
O	Hot-setting thermoplastic resin modified with thermosetting resin and pigment
P	Hot-setting mixture of thermosetting (phenol) resin and synthetic rubber
Q	Hot-setting, two-component adhesive of liquid thermosetting resin and thermoplastic (polyvinyl) powder
Designation	Secondary glues
R	Hot-setting phenol-formaldehyde resin
S	Acid catalyzed phenol-formaldehyde resin
T	Resorcinol resin, room-temperature setting
U	Room-temperature-setting furane resin



TABLE 3. - TENSILE STRENGTH OF CORRUGATED HONEYCOMB STRUCTURES<sup>1</sup>

MADE WITH DIFFERENT GLUES AND GLUING CONDITIONS

Specimen designation (fig. 6)	Honeycomb structure	Primary glue (see appendix)	Secondary glue (see appendix)	Amount of spread	Curing temperature (°F)	Curing pressure	Tensile strength (psi)	Type of failure
A9I { A B C D	Chestnut chip	N	U	Heavy	160	Medium	60	Primary glue
	-----do-----	N	S	---do---	160	---do---	145	Do.
	-----do-----	P	U	---do---	160	---do---	107	Do.
	-----do-----	P	S	---do---	160	---do---	289	Do.
I4I { E F	Kraft	O	S	Medium	120 to 150	---do---	340	Secondary glue
	-----do-----	O	S	Heavy	120 to 150	---do---	398	Secondary glue and core
C5I G	Glass fiber and kraft	O	S	Medium	120 to 150	---do---	386	Secondary glue
A9I { H I J K	Chestnut chip	Q	U	Heavy	160	---do---	410	Do.
	-----do-----	Q	S	---do---	160	---do---	525	Core
	-----do-----	O	U	---do---	160	---do---	161	Primary glue
	-----do-----	O	S	---do---	160	---do---	633	Core
B4I { L M	Mitscherlich	Q	S	---do---	140 to 150	Low	210	Core
	-----do-----	Q	U	---do---	140 to 150	---do---	268	Do.
A9I { N O P Q R S	Chestnut chip	O	S	Medium	140 to 150	---do---	357	Secondary glue
	-----do-----	O	S	Heavy	140 to 150	---do---	390	Core
	-----do-----	O	T	Medium	140 to 150	---do---	461	Primary glue
	-----do-----	O	T	Heavy	140 to 150	---do---	366	Core and glue
	-----do-----	O	S	---do---	220	---do---	460	Core
	-----do-----	Q	S	---do---	220	---do---	513	Do.
	-----do-----	Q	S	---do---	220	---do---	513	Do.

<sup>1</sup>All core specimens were 1 by 1 inch in cross section and 1/2 inch long in the direction of the cells, except specimens R and S which were 1 inch long.

TABLE 4. - COMPRESSIVE STRENGTH OF HONEYCOMB STRUCTURES<sup>1</sup> WITH DIFFERENT RESIN CONTENTS

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Approximate resin <sup>2</sup> content	Apparent specific gravity of core <sup>3</sup>	Compressive properties <sup>4</sup>						
		Ultimate strength	Ultimate strength divided by apparent specific gravity	Ultimate strength corrected to specific gravity of 0.153	Stress at proportional limit	Stress at proportional limit divided by apparent specific gravity	Modulus of elasticity	Modulus of elasticity divided by apparent specific gravity
(percent)		(psi)	(psi)		(psi)	(psi)	(psi)	(psi)
45	0.146	1,082	7,367	7,620	411	2,801	99,660	678,500
50	.157	1,438	9,100	8,940	560	3,546	122,050	773,300
55	.173	1,752	10,140	9,340	530	3,190	115,900	671,000

<sup>1</sup>Nine-mil chestnut chip paper (A9) was used.



<sup>2</sup>Resin F (table 2).

<sup>3</sup>Based on weight and volume (determined by over-all dimensions) at 75° F and 65 percent relative humidity.

<sup>4</sup>Specimen size was approximately 2 by 2 by 8 inches; load was applied parallel to the direction of the cell openings; deformation was measured over a 2-inch gage length.

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TABLE 5. - COMPRESSIVE PROPERTIES OF HONEYCOMB STRUCTURES MADE FROM SEVERAL TYPES OF PAPER

Type of paper	Structure	Resin <sup>1</sup> content  (percent)	Apparent specific gravity of core <sup>2</sup>	Compressive properties <sup>3</sup>				
				Ultimate strength  (psi)	Ultimate strength divided by apparent specific gravity  (psi)	Ultimate strength corrected to specific gravity of 0.153 (psi)	Modulus of elasticity  (psi)	Modulus of elasticity divided by apparent specific gravity  (psi)
Chestnut chip (9-mil)	A9I	52	0.160	695	4,330	4,200	68,900	429,000
Mitscherlich (3-mil)	B4I	49	.095	340	3,560	4,890	62,000	649,000
Glass fiber and kraft mixture (5-mil)	C5I	53	.121	559	4,610	5,390	83,200	688,000
High-strength kraft (4-mil)	D4I	45	.143	735	5,120	5,360	79,600	555,000
High-strength kraft (6-mil)	E6I	48	.151	799	5,160	5,200	89,100	590,000
High-strength kraft (8-mil)	F8I	54	.181	982	5,410	4,840	106,800	589,000
High-strength kraft (10-mil)	G10I	49	.212	1,293	6,100	4,910	140,000	660,000

<sup>1</sup>Resin I (appendix).<sup>2</sup>Based on weight and volume (determined by over-all dimensions) at 75° F and 65 percent relative humidity.<sup>3</sup>Specimen size was approximately 2 by 2 by 8 inches; load was applied in the direction of the corrugations; deformations were measured over a 2-inch gage length.

TABLE 6. - COMPRESSIVE STRENGTH OF HONEYCOMB STRUCTURES<sup>1</sup> MADE WITH SEVEN DIFFERENT CONTACT RESINS

Type of structure	Resin content of core  (percent)	Apparent specific gravity of core <sup>2</sup>	Compressive properties <sup>3</sup>						
			Ultimate strength  (psi)	Ultimate strength divided by apparent specific gravity  (psi)	Ultimate strength corrected to specific gravity 0.153  (psi)	Stress at proportional limit  (psi)	Stress at proportional limit divided by apparent specific gravity  (psi)	Modulus of elasticity  (psi)	Modulus of elasticity divided by apparent specific gravity  (psi)
A9F	53.5	0.173	1,752	10,140	9,320	550	3,190	115,900	671,000
A9E	48.5	.146	1,158	7,910	8,170	440	2,730	102,000	697,000
A9J	49.0	.152	1,048	6,900	6,940	295	1,940	84,900	559,000
A9G	47.5	.151	1,081	7,150	7,210	345	2,280	82,900	549,000
A9M	53.0	.172	921	5,360	4,960	243	1,410	79,100	461,000
A9I	51.5	.160	695	4,330	4,200	258	1,610	68,900	429,000
A9H	50.0	.157	703	4,470	4,550	263	1,670	67,100	426,000

<sup>1</sup>Nine-mil chestnut chip paper (A9) was used.

<sup>2</sup>Based on weight and volume (determined by over-all dimension) at 75° F and 65 percent relative humidity.

<sup>3</sup>Specimen size was approximately 2 by 2 by 8 inches; load was applied parallel to the direction of cell openings; deformations were measured over a 2-inch gage length; average values are from five tests.



TABLE 7. - COMPRESSIVE PROPERTIES OF HONEYCOMB STRUCTURES (D4AJ) MADE OF 4-MIL KRAFT PAPER  
TREATED WITH VARIOUS AMOUNTS OF PHENOL RESIN BEFORE CORRUGATING

Amount of phenol resin used in pre- treat- ment <sup>1</sup>  (percent)	Apparent specific gravity of core <sup>2</sup>	Compressive properties <sup>3</sup>					
		Ultimate strength	Ultimate strength divided by apparent specific gravity	Stress at propor- tional limit	Stress at propor- tional limit divided by apparent specific gravity (psi)	Modulus of elas- ticity  (psi)	Modulus of elasticity divided by apparent specific gravity  (psi)
0	0.111	653	5,800	323	2,860	72,800	655,000
11.0	.106	956	8,221	374	3,218	80,770	694,800
20.6	.116	874	7,523	331	2,841	80,060	689,400

<sup>1</sup>Enough contact resin J (appendix) was added after corrugating to produce a honeycomb core material with a total resin content of approximately 55 percent.

<sup>2</sup>Based on weight and volume (determined by over-all dimensions) at 75° F and 65 percent relative humidity.

<sup>3</sup>Specimen size was approximately 2 by 2 by 8 inches; load was applied parallel to the direction of the cell opening; deformations were measured over a 2-inch gage length.



TABLE 8. - PARTIAL EVALUATION OF MECHANICAL PROPERTIES OF HONEYCOMB STRUCTURES

MADE OF CORRUGATED PAPER IMPREGNATED WITH RESIN<sup>a</sup>

Type of test	Type of structure	Apparent specific gravity <sup>b</sup>	Ultimate strength (psi)	Ultimate strength divided by apparent specific gravity (psi)	Stress at proportional limit (psi)	Stress at proportional limit divided by apparent specific gravity (psi)	Modulus of elasticity (c) (psi)	Modulus of elasticity divided by apparent specific gravity (c) (psi)
Compression - parallel to length of cells (L)	H3AF	0.070	368	5,250	180	2,570	47,200	674,000
	H3AF	.080	400	5,000	194	2,425	48,500	606,000
	I4AF	.100	492	4,920	191	1,910	72,500	725,000
	J6AF	.106	478	4,510	193	1,820	71,450	673,000
	E6AF	.138	1,014	7,350	463	3,355	100,500	728,000
Compression - perpendicular to length of cells and parallel to plane of corrugated sheet (T)	H3AF	.070	5.3	75.7	2.2	31.4	64.4	920
	H3AF	.080	5.7	71.2	2.2	27.5	67.2	840
	I4AF	.100	8.7	87.0	2.7	27.0	110.9	1,109
	J6AF	.106	7.9	74.5	2.7	25.5	108.1	1,020
	E6AF	.138	30.7	226.5	10.2	75.0	467.1	3,435
Compression - perpendicular to length of cells and perpendicular to plane of corrugated sheet (R)	H3AF	.070	4.1	58.5	1.3	18.6	41.6	595
	H3AF	.080	3.8	47.5	1.9	23.7	43.7	546
	I4AF	.100	6.6	66.0	2.3	23.0	101.1	1,011
	J6AF	.106	6.9	65.1	2.1	19.8	87.4	825
	E6AF	.138	21.4	155.0	7.4	53.6	357.0	2,585
Tension - parallel to length of cells (L)	H3AF	.070	324	4,630	d <sub>0</sub>	-----	-----	-----
	H3AF	.080	164	2,050	d <sub>3</sub>	-----	-----	-----
	I4AF	.100	343	3,430	d <sub>79</sub>	-----	-----	-----
	J6AF	.106	282	2,660	d <sub>86</sub>	-----	-----	-----
	E6AF	.138	578	4,190	d <sub>6</sub>	-----	-----	-----
Shear deformation in plane parallel to length of cells and parallel to plane of corrugated sheet (LT)	H3AF	.070	181	2,570	133	1,900	15,730	225,000
	H3AF	.080	176	2,200	127	1,590	15,870	198,000
	I4AF	.100	268	2,680	128	1,280	17,740	177,400
	J6AF	.106	281	2,650	195	1,840	18,250	172,000
	E6AF	.138	321	2,320	176	1,280	33,810	245,000
Shear deformation in plane parallel to length of cells and perpendicular to plane of corrugated sheet (LR)	H3AF	.070	145	2,070	102	1,460	8,860	127,000
	H3AF	.080	143	1,790	83	1,040	9,200	115,000
	I4AF	.100	206	2,060	122	1,220	11,650	116,500
	J6AF	.106	207	1,950	115	1,090	16,680	157,000
	E6AF	.138	317	2,300	175	1,270	18,510	134,000

<sup>a</sup>Resin F of appendix.<sup>b</sup>Based on weight and volume (determined by over-all dimensions) at 75° F and 65 percent relative humidity.<sup>c</sup>For shear values, modulus of rigidity.<sup>d</sup>Percent glue failure in test specimens.

TABLE 9. - MECHANICAL PROPERTIES OF SOME LOW-DENSITY CORE MATERIALS HAVING APPROXIMATELY 0.1 SPECIFIC GRAVITY<sup>a</sup>

[Data from Forest Products Laboratory tests]

Core material	Compression									Ultimate tension		
	Longitudinal			Radial			Tangential			Longi- tudinal	Radial	Tangen- tial
	Ultimate	Proportional limit stress	Modulus of elasticity	Ultimate	Proportional limit stress	Modulus of elasticity	Ultimate	Proportional limit stress	Modulus of elasticity			
Balsa wood	960	580	330,000	<sup>b</sup> 90	30	17,000	<sup>b</sup> 70	20	5,700	<sup>c</sup> 1,200	<sup>d</sup> 85	<sup>d</sup> 120
Honeycomb paper <sup>e</sup>	490	100	72,500	7	2	100	9	3	110	<sup>c</sup> 340	-----	-----
Cellular cellulose acetate <sup>f</sup>	65	35	4,000	-----	-----	17,000	120	65	16,000	-----	<sup>c</sup> 300	-----
Cellular hard rubber (Hycar) <sup>f</sup>	110	50	6,000	90	20	1,600	65	13	11,000	-----	<sup>c</sup> 250	-----
Honeycomb glass cloth <sup>e</sup>	-----	-----	100,000	-----	1	35	-----	3	125	<sup>a</sup> 500-700	-----	-----

Core material	Shear						Poisson's ratios					
	Ultimate			Modulus of rigidity			LT	LR	RT	TR	TL	RL
	LT	LR	TR	LT	LR	TR						
Balsa wood	<sup>e</sup> 210	<sup>e</sup> 175	----	<sup>h</sup> 12,500	<sup>h</sup> 18,000	<sup>h</sup> 2,000	0.488	0.229	0.665	0.231	0.0092	0.0183
Honeycomb paper <sup>e</sup>	<sup>i</sup> 270	<sup>i</sup> 200	----	<sup>i</sup> 17,700	<sup>i</sup> 11,600	-----	-----	-----	-----	-----	-----	-----
Cellular cellulose acetate <sup>f</sup>	----	<sup>i</sup> 125	----	-----	<sup>i</sup> 3,500	-----	.206	.087	-----	.390	-----	-----
Cellular hard rubber (Hycar) <sup>f</sup>	----	<sup>i</sup> 125	----	<sup>i</sup> 4,000	<sup>i</sup> 4,000	-----	.398	-----	.342	-----	-----	-----
Honeycomb glass cloth <sup>e</sup>	<sup>i</sup> 85	<sup>i</sup> 105	----	<sup>i</sup> 3,800	<sup>i</sup> 12,700	-----	-----	-----	-----	-----	-----	-----

<sup>a</sup>All values other than Poisson's ratios are in pounds per square inch. Data shown have been determined from various test procedures, some of which have been revised subsequently.

<sup>b</sup>Stress at 0.1-inch strain.

<sup>c</sup>Test specimens 1 by 1 by 1/2 inch glued to aluminum cubes. Failures took place in core, glue lines, or partly in each.

<sup>d</sup>Standard wood test specimens (reference 2, p. 24).

<sup>e</sup>Direction of cells, (L); direction of corrugated sheets, (T); perpendicular to cells and corrugated sheets, (R).

<sup>f</sup>Extruded or formed length, (L); width of block, (T); thickness of block, (R).

<sup>g</sup>Block shear tests (reference 2, p. 88).

<sup>h</sup>Determined from plate shear tests (reference 3).

<sup>i</sup>Frame shear tests.







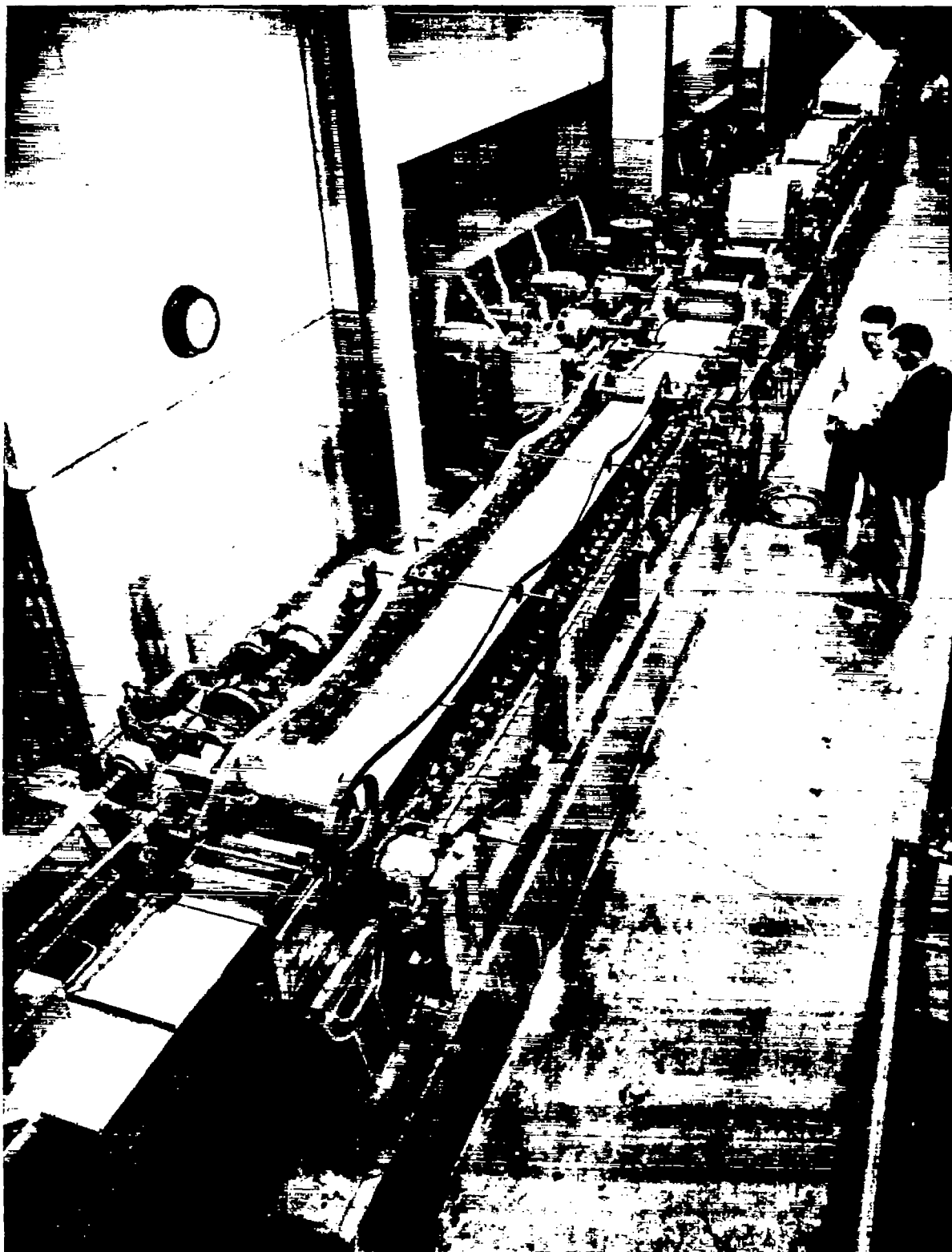


Figure 1.- Forest Products Laboratory experimental Fourdrinier paper machine.



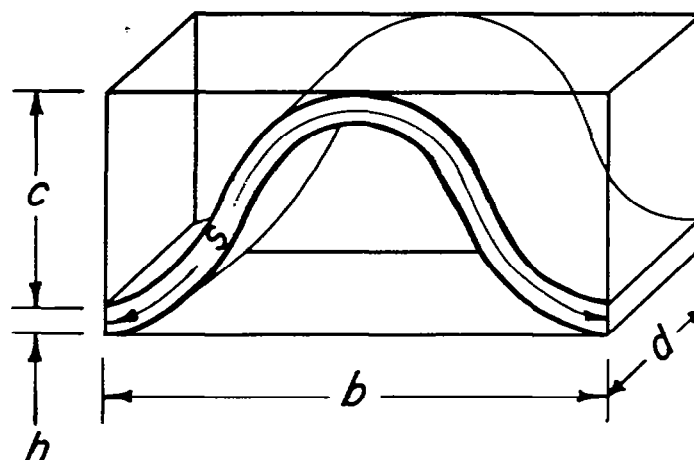


Figure 2.- Sketch of an element of a honeycomb structure.

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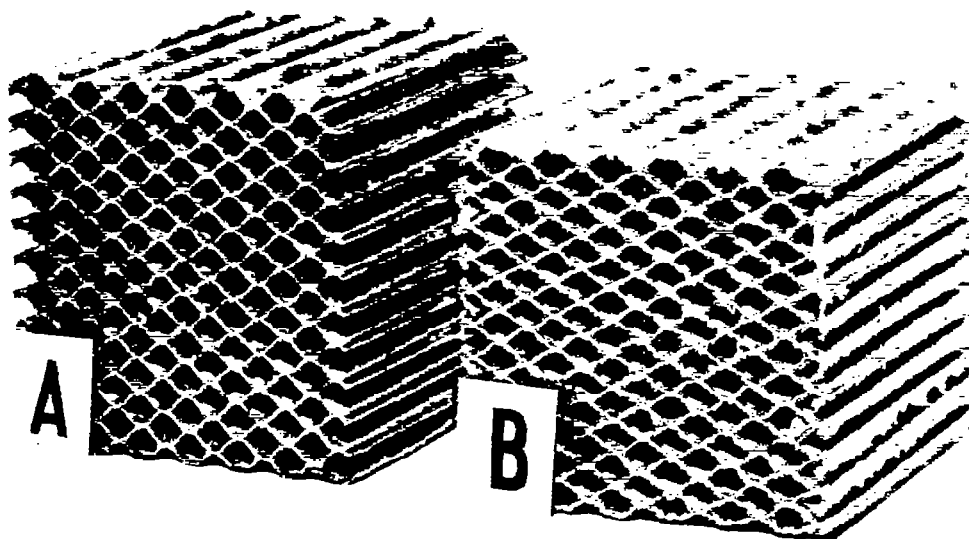


Figure 3.- Cell size and shape of honeycomb core material when the base paper is (A) treated (before corrugating) with 18 percent water-soluble phenol resin and (B) untreated. The pretreated material retains its corrugations while the untreated tends to flatten.

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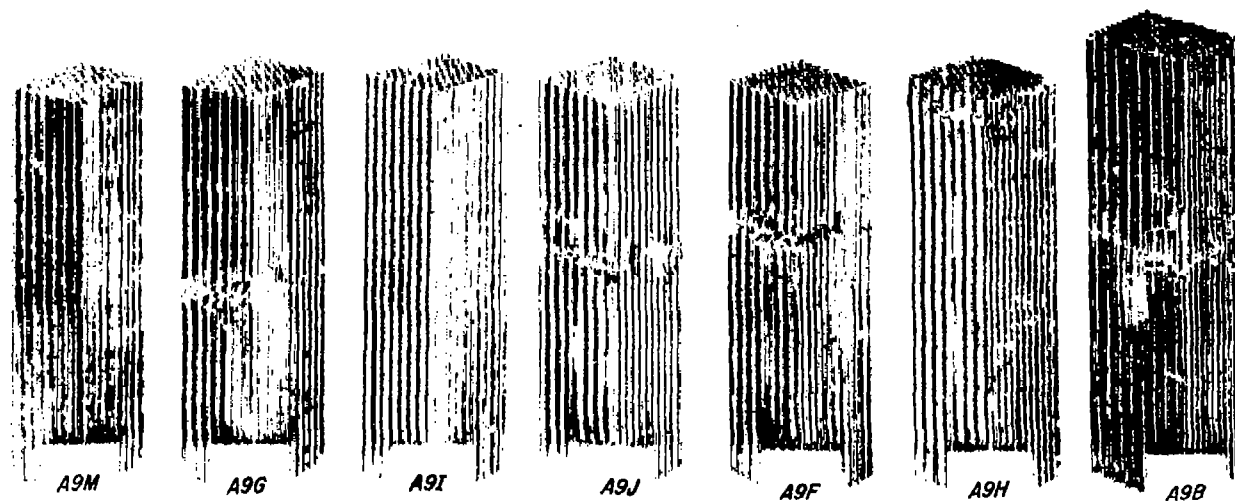


Figure 4.- Typical compression failures for honeycomb core materials made with seven different contact resins. For key to designations, see table 6.

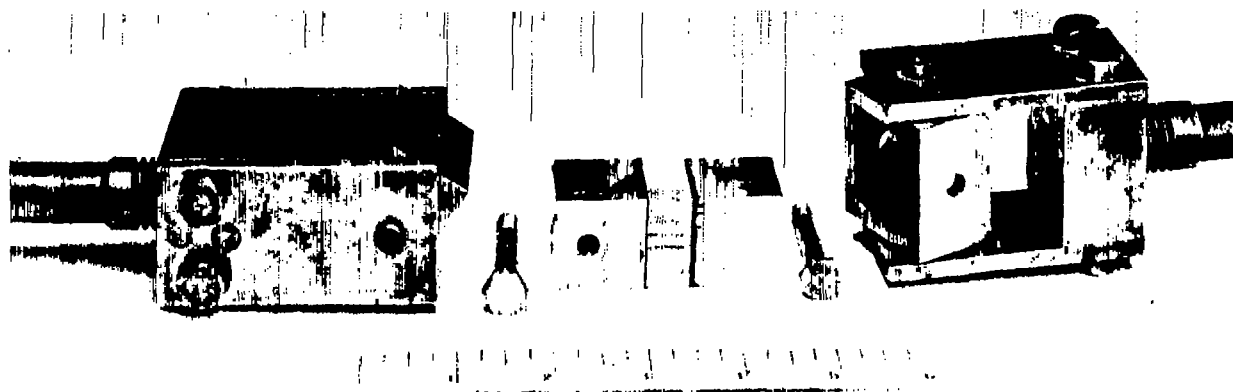


Figure 5.- Tensile-strength test apparatus for sandwich core material, shown disassembled. Core material, glued to loading blocks, is shown in center.





Figure 6.- Representative failures of honeycomb core materials used in exploratory studies for development of a satisfactory tensile-strength specimen. Identification of each specimen is given in table 3. Specimens shown were made with corrugated materials.







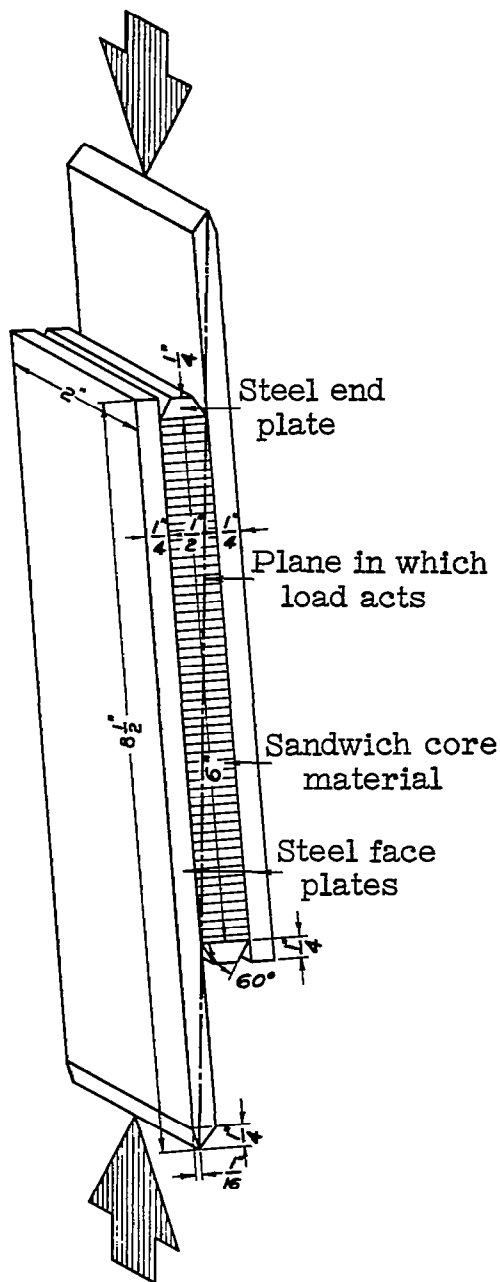


Figure 7.- Frame shear apparatus for testing of low-density core materials. Specimen is glued to steel side and end plates.

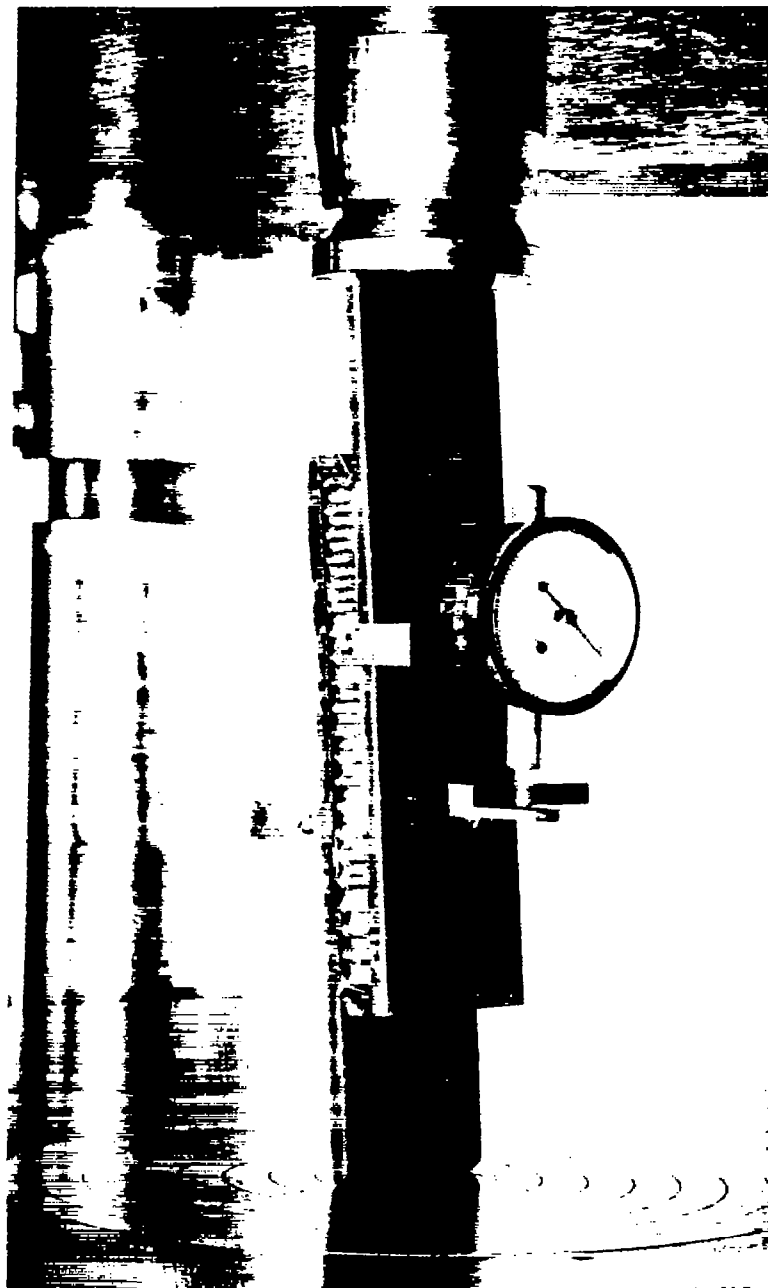


Figure 8.- A shear specimen of honeycomb core material under load, showing position of a dial gage to measure deformation. Pressure is being exerted downward. Many failures were at glue line between specimen and metal end and side plates of apparatus.





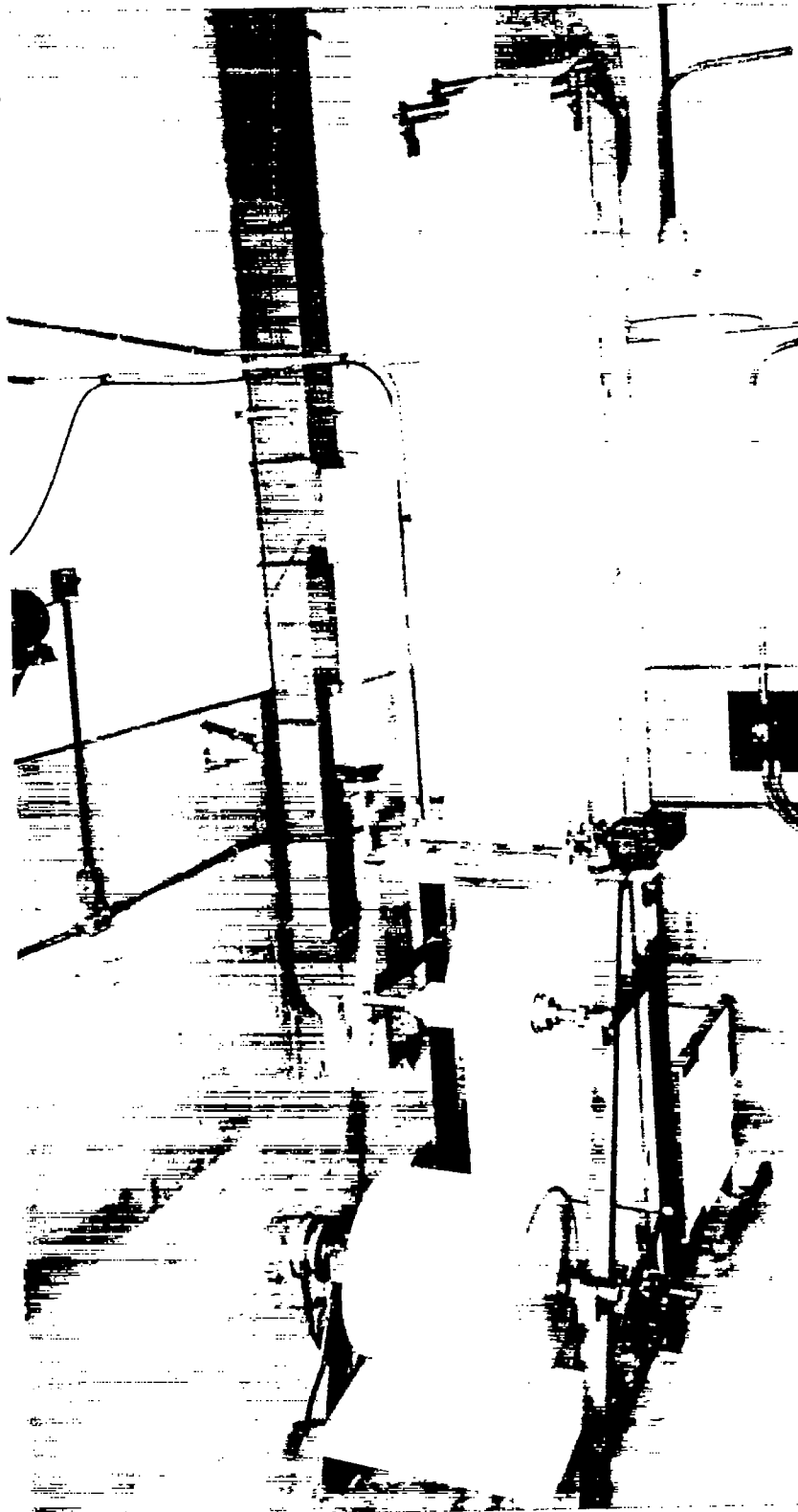


Figure 9.- Forest Products Laboratory experimental resin-impregnating equipment.



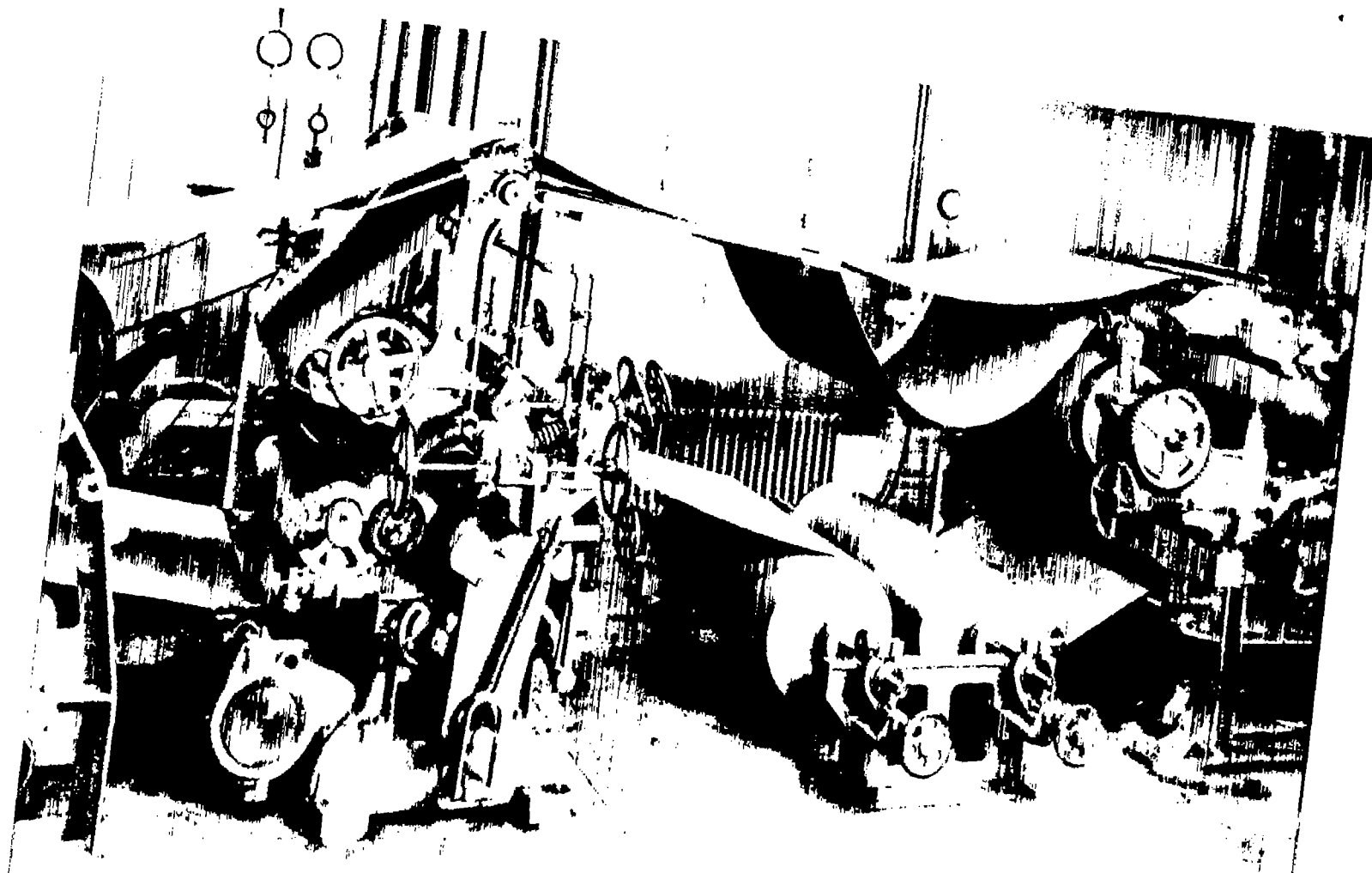


Figure 10.- Forest Products Laboratory experimental corrugating machine.



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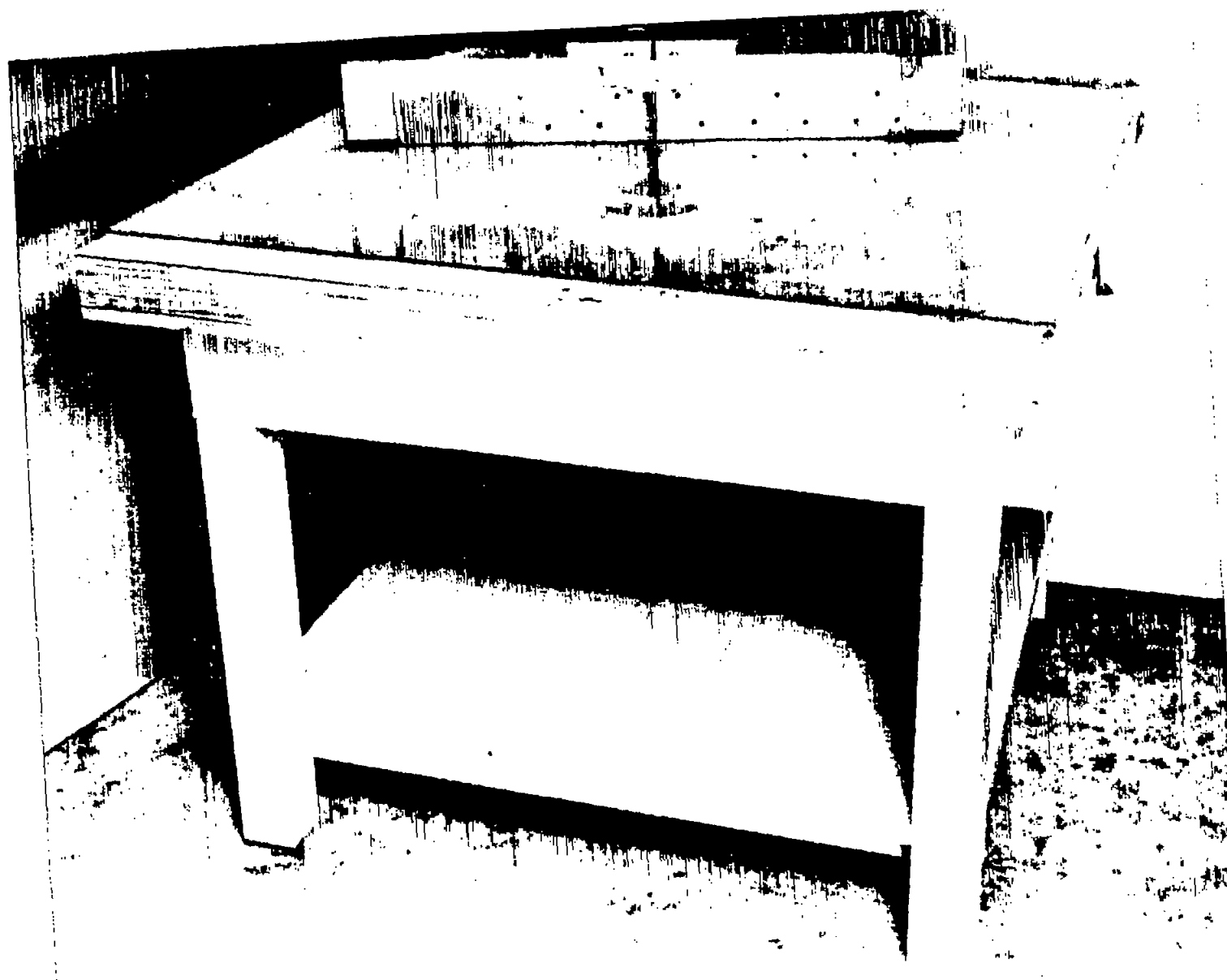


Figure 11.- Plate-glass surface and adjustable doctor blade for applying contact resin to corrugated paper.

